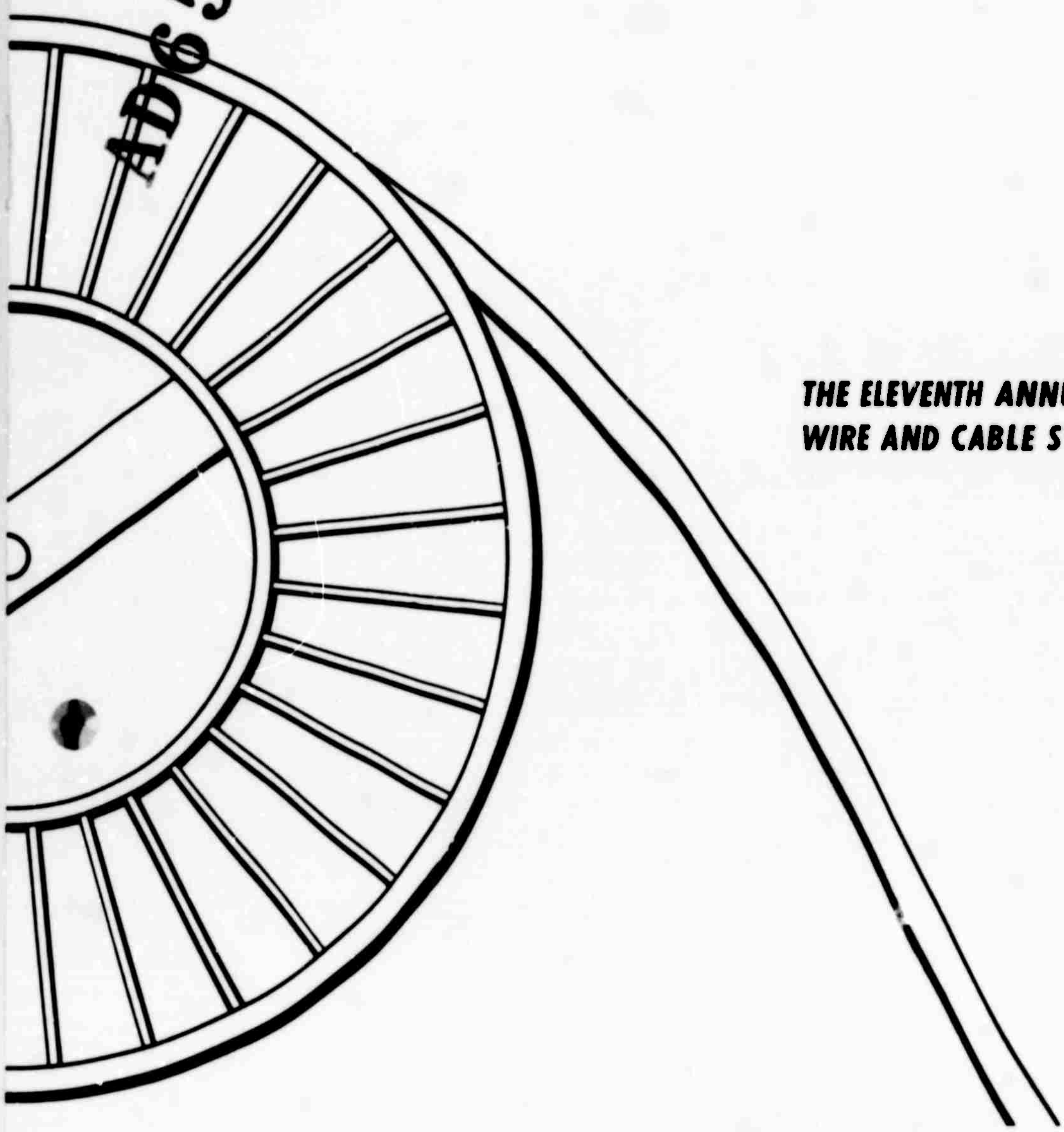

THE ELEVENTH ANNUAL
WIRE AND CABLE SYMPOSIUM

THE COOLING RATE OF POLYETHYLENE INSULATED WIRE DURING THE EXTRUSION PROCESS

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INTRODUCTION

During the manufacture of polyethylene insulated conductors, hot polyethylene is applied to the copper conductor in the head of an extruder. Immediately after the insulated conductor leaves the extruder head, it is cooled in a trough filled with water. The ~~purpose of~~ this paper ~~is to~~ present a method to determine the cooling rate of the polyethylene insulation as it passes through the water trough.

It is desirable to determine the cooling rate for the following reasons:

1. To design the cooling trough length so that the insulation will not suffer plastic deformation in passing over the turn-around sheaves at the end of the water trough.

2. To permit calculation of the temperature of the insulation at the point it passes through the capacitance monitor electrode. The coaxial capacitance can then be calculated using the temperature distribution.

3. To determine the effect of radial temperature gradients within the insulation on extrusion-sensitive properties of the plastic such as low temperature brittleness and elongation.

Early work on this problem was done in connection with the extrusion of the core for the first transatlantic telephone cable (Ref. 1). In this cable the copper conductor size was 0.16 inch and the DOD (diameter over dielectric) was 0.62 inch. The necessary cooling time was approximately 10 minutes with a wire speed of 42 fpm. The extrusion process was controlled by a capacitance monitor (Ref. 2) so that it was necessary to determine the tempera ·re at the point where it passed through the probe. It was determined by a series of experiments that a simple exponential formula gave a good approximation to the "average"* temperature of the polyethylene.

* "Average" temperature refers to the uniform temperature that the insulation must have to give the corresponding deviation from ambient capacitance. Actually there is a temperature gradient in the polyethylene.

Experiments made on 19 gauge polyethylene insulated conductors showed, however, that a simple exponential formula did not give a good approximation to the average temperature. Therefore a general analytical solution to the problem of cooling an insulated wire in a water trough was developed. The solution permits calculation of the temperature at any point in the insulation after any cooling time. The purpose of this paper is to describe some of the interesting aspects of the problem and to present some of the results of the calculations.

SOLUTION FOR TEMPERATURE DISTRIBUTION

Figure 1 describes the cooling process that takes place when the conductor enters the cooling water. Heat, which is stored in the polyethylene and copper, is transferred to the water. This is the radial heat transfer, Q_R. The insulation and copper at point 2 will be at a lower temperature than at point 1 due to the radial heat transfer. The temperature gradient will cause heat transfer in the longitudinal direction but it will be small compared to the radial heat transfer.

Neglecting the heat transfer in the longitudinal direction and assuming that the thermal conductivity, density, and specific heat are constant with temperature*, the differential equation (Ref. 3) that applies to the cooling process described above is:

$$\frac{\partial^2 t}{\partial r^2} + \frac{1}{r}\frac{\partial t}{\partial r} = \frac{1}{\alpha}\frac{\partial t}{\partial \theta}, \tag{1}$$

where

t = temperature

r = radius

θ = time

α = $K/\rho C$ = thermal diffusivity

K = thermal conductivity

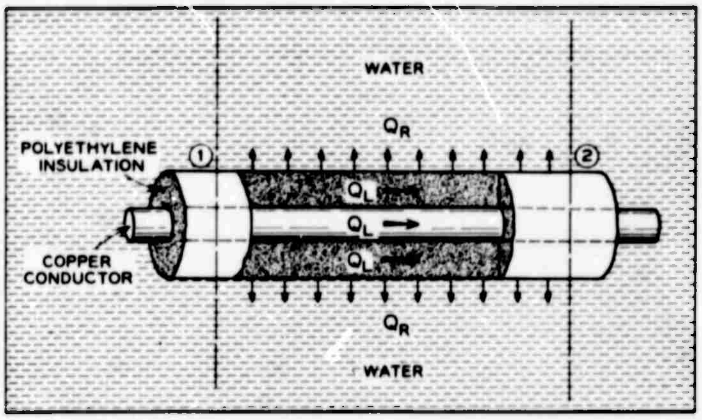
ρ = density

C = specific heat.

The solution for the above differential equation with the appropriate boundary conditions is very complex and is beyond the scope of this paper. It involves the expansion of the eigenfunction in an infinite series. Each term in the infinite series is the product of a Bessel function term and an exponential decay term.

The solution is useful for obtaining numerical results only when it is programmed for evaluation on a high-speed digital computer. It was programmed for Bell Laboratories IBM 7090 computer at Murray Hill, N. J. and numerical results were obtained for several special cases. Before the numerical results for these special cases are discussed it should be pointed out just what parameters determine the cooling rate of the insulation.

*This assumption is not completely true and it will be discussed in a later section.



Q_L = HEAT TRANSFER IN LONGITUDINAL DIRECTION

Q_R = HEAT TRANSFER IN RADIAL DIRECTION

Figure 1 - Heat conduction from plastic-insulated conductor to cooling water

Besides the radius and the cooling time the temperature of the polyethylene depends upon the following properties of the conductor:

1. The ratio of the copper conductor diameter to the DOD.

2. The initial temperature of the polyethylene and copper.

3. The thermal properties of the materials.

In other words the size, material, and extrusion conditions that are used to make an insulated conductor must be specified. Since it was desirable to check the mathematical solution to this heat transfer problem, the standard 19 gauge 60 mil DOD polyethylene insulated conductor was selected as a physical model which could readily be duplicated on the extruder in the laboratory at Murray Hill. The initial temperature of the insulation was determined from the polyethylene temperature in the extruder. This was chosen to be 412°F. Two initial copper temperatures were used. These were 412°F and 80°F. The material used for the insulation was low-density branched polyethylene. The thermal properties of the polyethylene and the copper are given in the next section.

THERMAL PROPERTIES OF POLYETHYLENE AND COPPER

In order to obtain a mathematical solution for the temperature distribution, the assumption was made that the thermal conductivity, density, and specific heat of polyethylene were constant with respect to temperature. Unfortunately, this is not true for the polyethylene. The specific heat, thermal conductivity, and density change quite substantially with temperature. In Figures 2 through 4, these parameters are plotted against temperature (Ref. 4). Since the parameters are not constant, the solution was obtained by choosing an average value for them over the temperature range of interest.

The specific heat, thermal conductivity, and density of copper are, for practical purposes, constant in the temperature range between 80°F and 412°F.

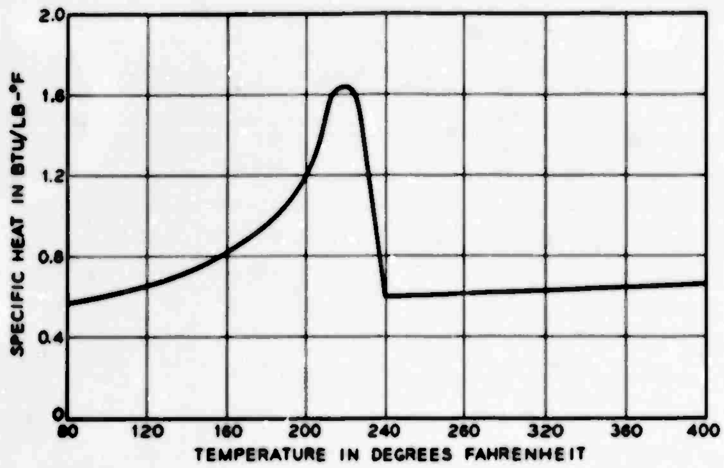


Figure 2 - Specific heat for 0.92-density branched polyethylene

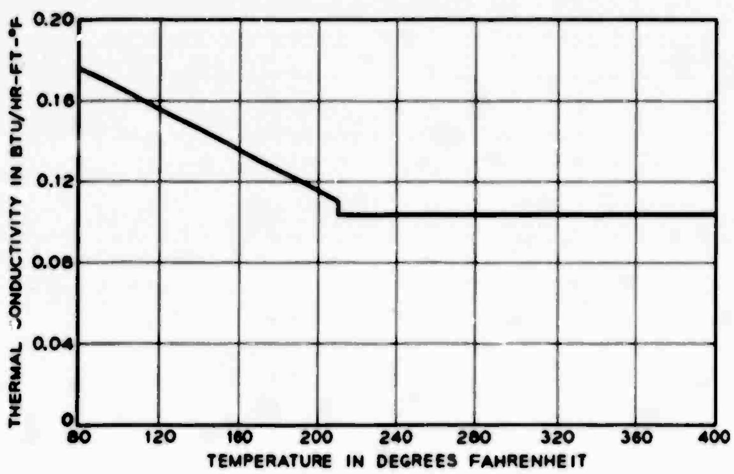


Figure 3 - Thermal conductivity for 0.92-density branched polyethylene

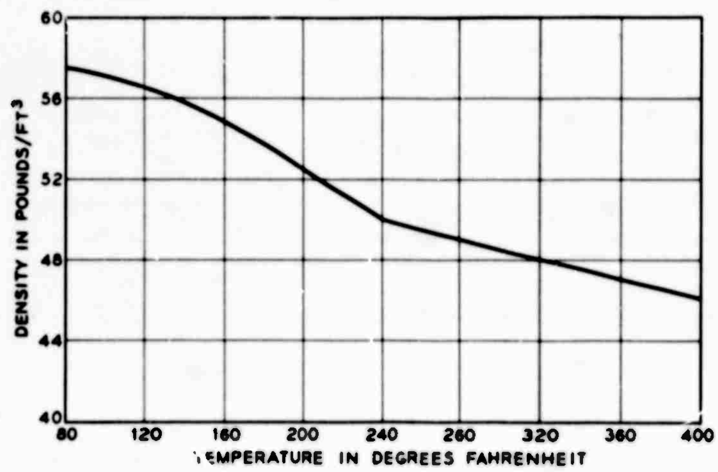


Figure 4 - Density for branched polyethylene

NUMERICAL RESULTS FOR 60-MIL DOD CONDUCTOR

Figures 5 and 6 show the exact solution to the problem for a 19-gauge 60-mil DOD polyethylene insulated conductor for the preheat conditions of 412° F and 80° F respectively. In the copper region of the conductor (0 to 18 mil radius) the temperature profile is flat. This was expected because the thermal conductivity of copper is about 2000 times greater than that of polyethylene. In the insulation region of the conductor (18 to 30 mil radius) the temperature distribution is much more complex and the cooling rate is affected by the preheat temperature. This can be seen by examining the temperature profiles at 0.5 second. The temperature of the insulation with preheat is almost twice as great as that of the wire with no preheat, at corresponding radii.

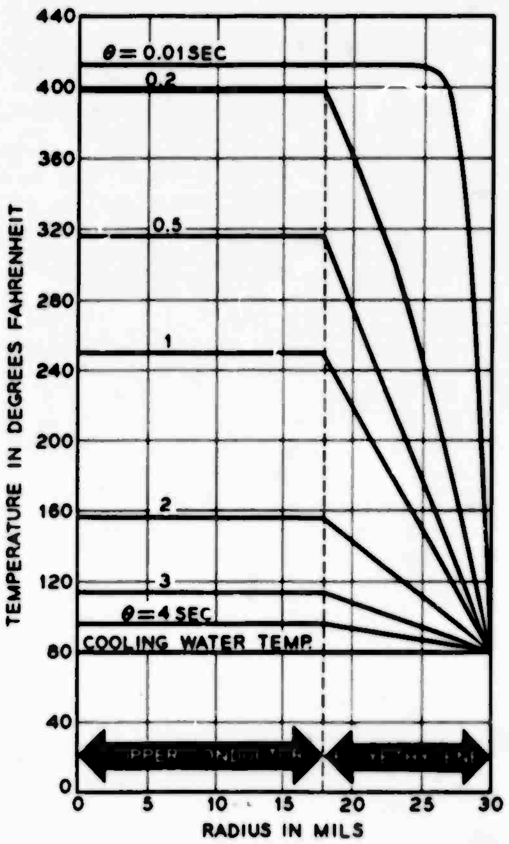


Figure 5 - Calculated temperatures. (Preheat 412° F)

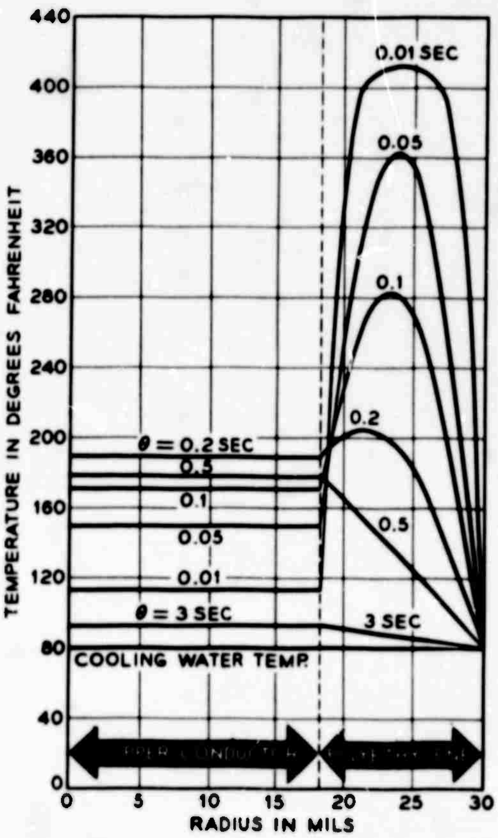


Figure 6 - Calculated temperatures. (Preheat 80° F)

The temperature distribution within the polyethylene approached a linear distribution after 0.5 second for the 80° F preheated conductor and after 0.2 second for the 412° F preheated conductor. The temperature for times greater than those above can be represented by a simple equation, with excellent accuracy. This equation is:

$$t - t_o = D_1\left(1 - \frac{r}{30}\right) \exp\left(-D_2\theta\right). \qquad (2)$$

where

t = temperature (°F)

t_o = 80° F water temperature

θ = time (seconds)

r = radius (mils)

D_1 and D_2 are constants listed below

D_1 = 967.5		412° F Preheat
D_1 = 373.5		80° F Preheat
D_2 = .8091		80° F and 412° F Preheat

This simplified equation proved to be very useful when the capacitance was calculated from the temperature distribution.

The temperature at the midpoint of the insulation is shown in Figure 7 for the conditions of no preheat and preheat equal to the stock temperature. These curves again show the effect of preheat on the cooling rate of the insulation.

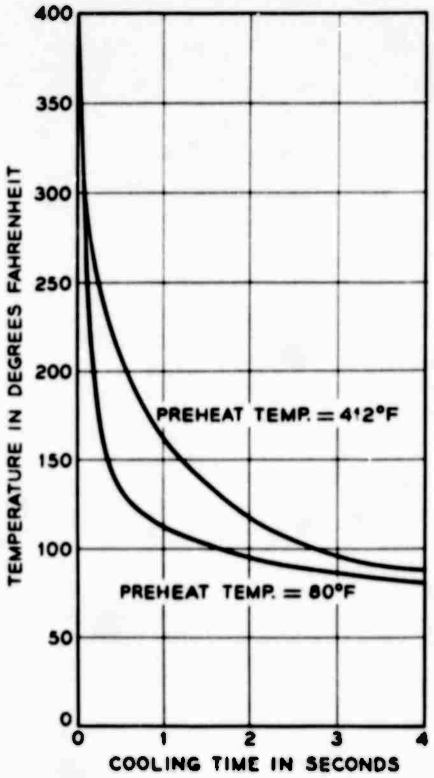


Figure 7 - Temperature at insulation midpoint

COAXIAL CAPACITANCE CALCULATED FROM TEMPERATURE DISTRIBUTION

In most transient heat transfer problems of this type it is not possible to check the solution directly, because of the difficulty of making the temperature measurements. However, in this problem there is one way to verify the temperature curves indirectly. This method is to calculate the coaxial capacitance from the temperature distribution and compare it with the measured coaxial capacitance. If the experimental and calculated coaxial capacitance agree, it will be a verification of the temperature curves.

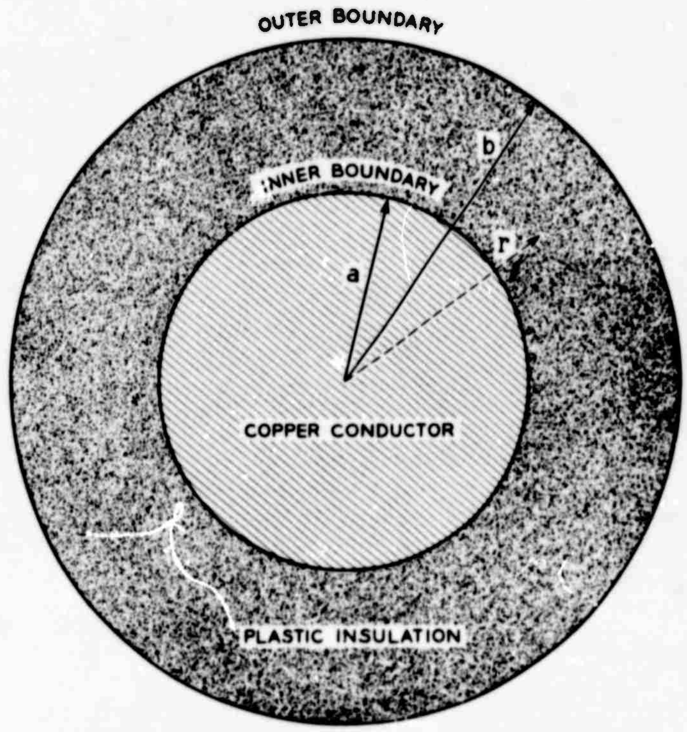


Figure 8 - Cross section of plastic-insulated conductor

RELATION BETWEEN DIELECTRIC CONSTANT AND CAPACITANCE

Normally, when the coaxial capacitance of a cylindrical conductor is calculated, the dielectric constant of the insulation is considered to be uniform. However, when there is a temperature gradient in the insulation, the dielectric constant is no longer uniform but varies as some function of the radius. In this case the general equation for the coaxial capacitance of a cylindrical conductor must be used. This equation is (see Figure 8):

$$C = \frac{2\pi}{\int_a^b \frac{dr}{r\,\epsilon(r)}} , \tag{3}$$

where

C = coaxial capacitance

r = variable radius

$\epsilon(r)$ = absolute dielectric constant (a function of radius)

a = conductor radius

b = insulation radius.

It can easily be shown that when the dielectric constant is uniform, equation (3) will be equivalent to,

$$C = \frac{2\pi\epsilon}{\ln \frac{b}{a}} , \tag{4}$$

which is the familiar equation for coaxial capacitance.

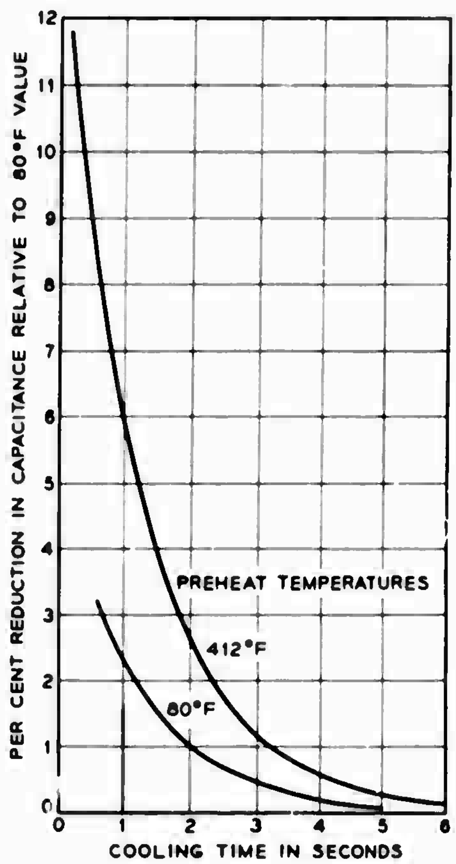


Figure 9 - Theoretical per cent changes in coaxial capacitance. (Ambient capacitance 75 $\mu\mu f$)

When the dielectric constant is not uniform, equation (4) is no longer applicable and equation (3) must be used with the proper function for the dielectric constant.

Experimental data have shown that the coaxial capacitance of a polyethylene insulated conductor is approximately a linear function of temperature. Using the temperature coefficient* of capacitance and the temperature of the insulation as a function of radius from Figures 5 and 6 [equation (2)], numerical answers were obtained from equation (3) for the 60-mil structure. The results are shown in Figure 9 for both preheat conditions. The ordinate axis is shown in percentages below the capacitance at water temperature (80°F).

The polyethylene dielectric constant used in the calculations was 2.25 and the coaxial temperature coefficient was 0.064 per cent/°F. The significance of preheat on the cooling rate is clearly demonstrated by the calculated coaxial capacitance. At 0.6 second the decrease in coaxial capacitance for the 80°F preheat temperature is 3.2 per cent and for the 412°F preheat temperature it is 8.4 per cent. This again demonstrates that the preheat temperatures have an important effect on the cooling time of the polyethylene.

EXPERIMENTAL VERIFICATION OF CALCULATIONS

As demonstrated above, the coaxial capacitance of an insulated wire conductor is determined by the temperature distribution within the insulation. The logical way to verify the temperature calculations is, therefore, to measure the coaxial capacitance of a wire while the wire is being extruded. This measurement was made at a series of points along the cooling trough, using a portable capacitance monitor. Since the capacitance of the wire is not completely constant, due to inadvertent small dimensional changes, a second capacitance monitor was placed at the far end of the water trough. This monitor was used to measure the small coaxial capacitance changes due to dimensional changes while running, thus permitting an accurate estimation of the change in capacitance due to temperature variations.

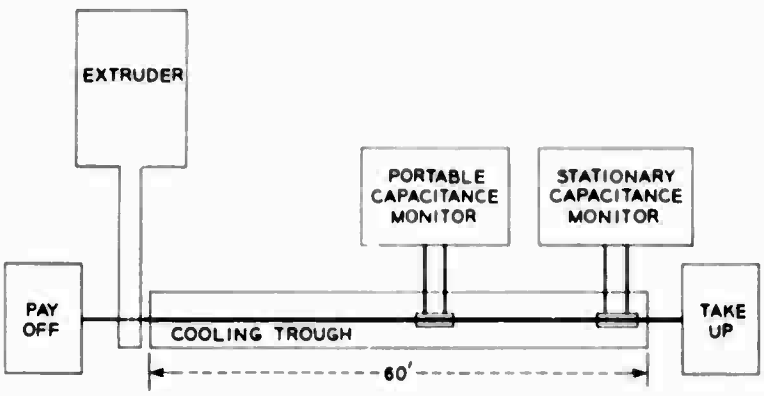


Figure 10 - Extrusion line for obtaining experimental capacitance data

*The coaxial capacitance temperature coefficient includes both expansion and dielectric constant change with temperature. The outer radius is therefore assumed to be constant.

The monitors were placed along the cooling trough as shown in Figure 10. All measurements were taken while the wire was being extruded at a constant speed of 600 ft/min.

The movable probe was initially placed as close as possible to the first probe to obtain a zero reference between the two probes. The portable probe was moved closer to the extruder head in three- to six-foot increments. The wire speed and distance from the extruder head to the movable probe was a measure of time. Throughout the experiments care was taken to maintain constant insulation, water, and preheat temperatures to match those used in the mathematical model. The results of these experiments are shown in Figure 11 compared to the calculated data shown previously in Figure 9. The upper pair of curves are for preheat temperatures of 412°F and the lower curves for a preheat temperature of 80°F. The dotted curves are the experimental data.

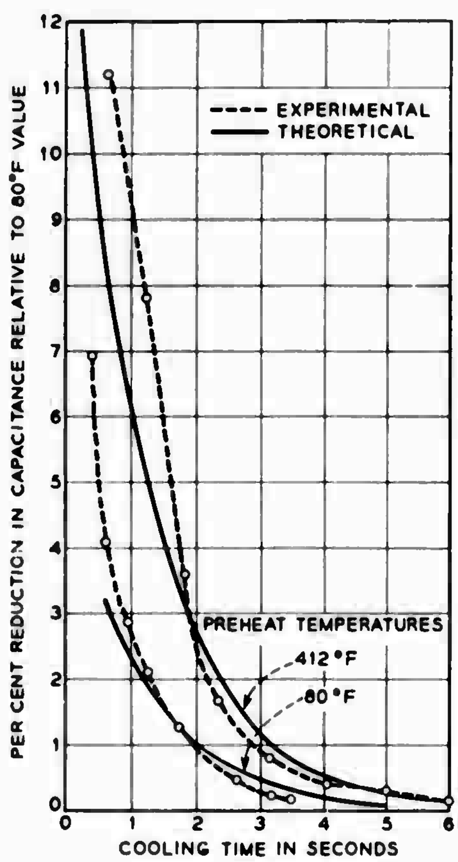


Figure 11 - Comparison of experimental and theoretical per cent changes in coaxial capacitance. (Ambient capacitance 75 $\mu\mu$f)

The experimental measurements compare quite closely to the calculated values except at very short cooling times. At the short cooling periods there are two reasons why the calculated values may be different from the experimental results.

1. The thermal properties of the material were averaged over the temperature range.

2. The coaxial temperature coefficient was determined only for temperatures up to 190°F.

The average value for the thermal properties was chosen over the temperature range. Actually the thermal conductivity is lower at the higher temperature and the specific heat is a maximum at the temperature 220°F. This would tend to give slower cooling initially than the temperature curves show. If this is the case the temperature will actually be higher than the calculated values at short cooling times. The maximum difference shown between the curves in Figure 11 is about 2 per cent. This would correspond to a uniform temperature error of 30°F or approximately 15 per cent of the average temperature. This is a very reasonable error, considering the assumptions that were made.

The second factor that may contribute to the capacitance error is the coaxial temperature coefficient. This coefficient was determined by measuring the change in capacitance of a sample submerged in hot water. The coefficient could not be measured above 190°F because air bubbles formed on the surface of the insulation at temperatures above 190°F. It is possible that above 190°F the coaxial temperature coefficient is no longer linear, due to the change of phase in the polyethylene. The decrease in density at the higher temperatures may decrease the capacitance much faster above 190°F than is shown by the linear relationship between temperature and capacitance.

NORMALIZED COOLING CURVES

In a previous section the temperature distributions within the insulated conductor were computed for a model with specified dimensions. However, as was pointed out earlier, the temperature distribution depends only upon ratios of the thermal properties and dimensions of the sample. For given initial temperatures the cooling curves can, therefore, be normalized for copper and polyethylene to include all dimensions, as long as the DOD over d ratio remains constant.

The normalized cooling curves for a polyethylene insulated conductor are given in Figures 12 through 15, for DOD/d ratios of 1.67 and 3.59. For each ratio the curves are given for the conditions of no preheat (wire at 80°F ambient temperature); and for preheat temperature equal to the polyethylene stock temperature (410°F).

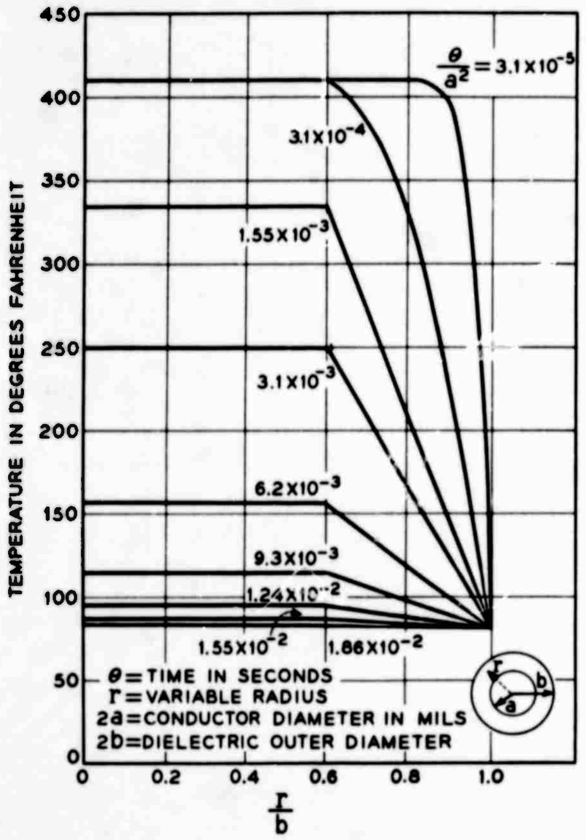


Figure 12 - Normalized cooling curves.
Stock temperature = 410° F
Preheat temperature = 410° F
DOD/d = 1.67

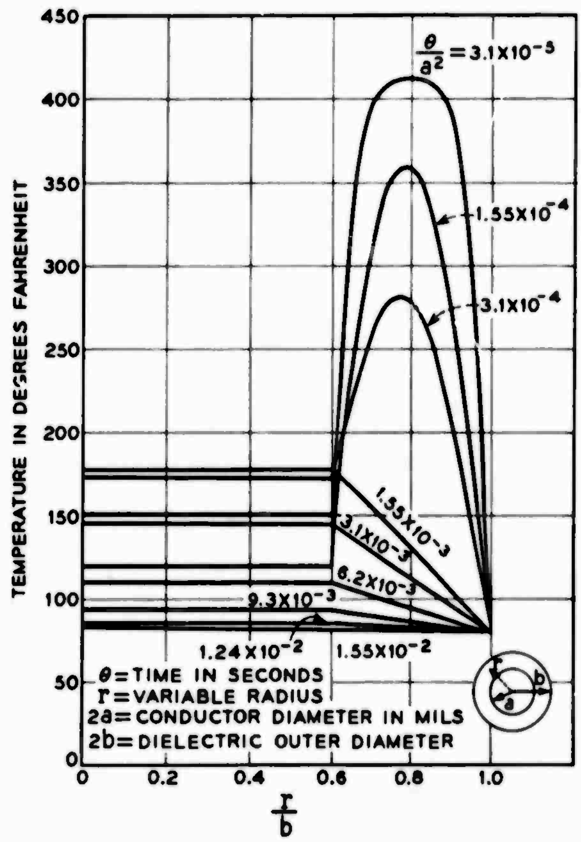


Figure 13 - Normalized cooling curves.
Stock temperature = 410° F
Preheat temperature = 80° F
DOD/d = 1.67

Each temperature curve is labeled with the number that represents the ratio (θ/a^2) of time in seconds to the square of the conductor radius in mils. The use of the illustrations is self-explanatory.

Several important conclusions can be drawn from the work on the cooling rate of a polyethylene insulated copper wire.

1. The temperature distribution within the insulation can be determined with fairly good accuracy by the solution to the heat transfer problem.

2. The coaxial capacitance can be calculated from the temperature distribution by use of the coaxial capacitance temperature coefficient.

3. The effect of preheat on the cooling time is appreciable, as demonstrated by the temperature curves and the coaxial capacitances.

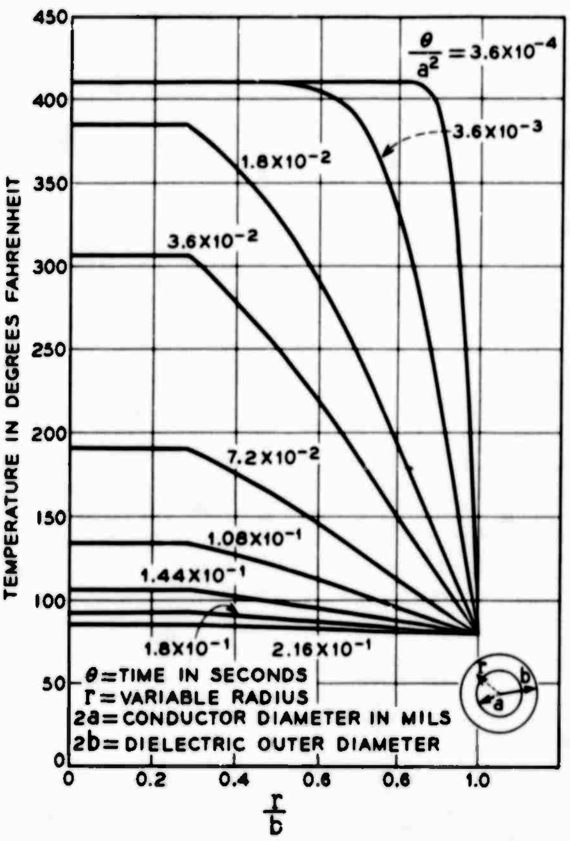


Figure 14 - Normalized cooling curves.
Stock temperature = 410° F
Preheat temperature = 410° F
DOD/d = 3.59

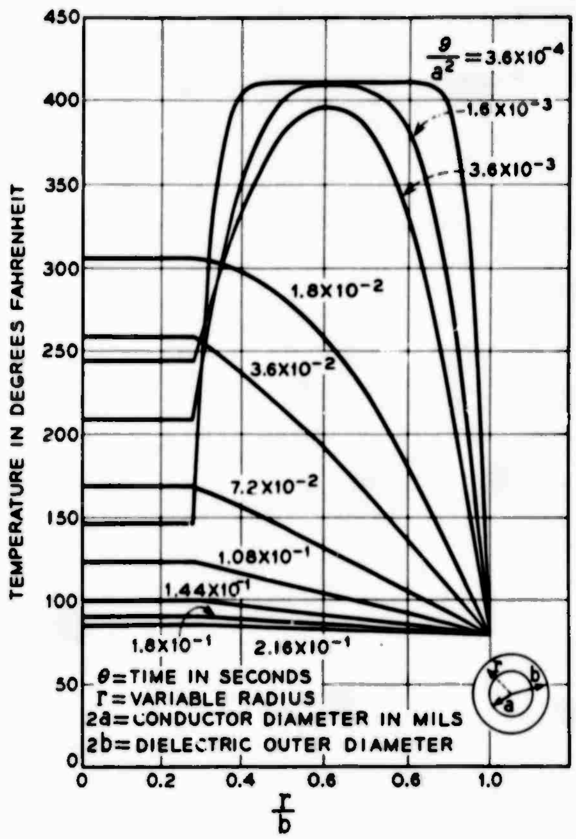


Figure 15 - Normalized cooling curves.
Stock temperature = 410° F
Preheat temperature = 80° F
DOD/d = 3.59

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